Indian J Phys **52A**, 100–113 (1978)

Investigation on the pulse-height distribution of electron avalanches generated by thermionically emitted electrons in a proportional counter

S. D CHATTERJEE, R. C. SASTRI* AND M DHARA

Indian Association for the Cultivation of Science, Jadavpur, Calcutta-700032

(*Received* 8 *February* 1977)

By releasing thermionically emitted single electrons with insufficient energy to produce immediate ionization in an Argon-Hydrogen proportional counter, it has been possible to study individual avalanche distribution in isolation from confusing effects arising from fluctuations in the number of primary ion pairs. The distribution in amplitude of the output pulses has been measured The shape of the distribution curve has been shown to correspond closely with theoretical curve of the general form $X^{(a-1)}\exp(b-cX)$ The line-widths of the avalanche pulses for thermionically emitted electrons at 873°K and 928°K have been calculated from the experimental data and compared with their corresponding theoretical values for mono-energetic electrons It is found that the mean pulse height increases for thermionically emitted electrons at higher temperatures although the voltage on the proportional counter is kept unaltered

1. INTRODUCTION

Proportional counters have been used in nuclear physics research for a long time, both in detecting ionizing particles and in measuring their energy. In most of the investigations of the past, the particles detected were strongly ionizing type, such as protons, alphas etc. and consequently the energy spent by the particles inside the counter was high. In the accounts of these investigations it had been often stated that, for the proper behaviour of proportional counters, the gas amplification factor must be below a maximum value 100. However, Curran *et al* (1949) showed that proportional counter operating in conjunction with an amplifier of high gain and good signal-to-noise performance can be used to measure accurately the energy of soft ionizing radiation such as β-rays emitted by H^3. The detection of relativistic electrons in proportional counter at high multiplification factor was earlier described in detail by Benson (1946). Pontecorvo *et al* (1949) demonstrated the practicability of the proportional counter with high gas amplification factor for counting Auger electrons. Hanna *et al* (1949) also described the essentials in their techniques in the investigation of L-Capture A^{37} and H^3 spectrum. Such a counter does not suffer from a dead time in the sense that a Geiger counter does and very rapid counting is theoretically possible.

* Permanent address : Department of Physics, Jadavpur University Calcutta-700032

Indeed Wilkinson (1950) has shown that the limit in the counting lies in the associated electronic circuits and not in the counter itself. He has also indicated that the total specific ionization S_t becomes very big for slow electrons. Thus by using the counter in the high proportional region the slow electrons are immensely favoured as compared to the cosmic-ray particles. In particular, the proportional counter can be regarded as a detector of 100 per cent efficiency for such radiations, possessing long plateaus of less slope than are usually obtained with Geiger tubes. This fact is important for several reasons among which may be noted the increased life of the proportional counter as compared with the life of a vapour-gas Geiger tube (factor 10^4 to 10^5) and the relative freedom from after pulses produced by bombardment of the cathode by positive ions liberated by the discharge.

It has been established that a proportional counter can operate satisfactorily at gas multiplications of 10^4 or perhaps more Thus with an amplifier capable of detecting down to, say, 2×10^3electrons at the first grid of the pre-amplifier, it should be possible to count single electrons liberated in the counter. Moreover, if the gas gain can be made sufficiently large without impairing the stability of the operation, the analysis of the energy spectrum of the pulses produced by single electrons can be carried through. Thus fundamental data concerning the statistical fluctuation of gas amplification can be obtained. The use of single electrons as the primary particles permits the separate study of this fluctuation in the absence of the complicating factors introduced by the variation in the number of ionpairs initially produced when homogeneous β-rays, X-rays or γ-rays are introduced Curran *et al* (1949) made a systematic study of the proportional counter when detecting single photo-electrons in order to clarify the statistics of multiplication process. Such information is important on account of its basic relation to the resolving power of the proportional counter tube as an analyser of radiation. A study of the pulse size distribution for single electrons enabled them to separate the contribution of the line-width due to gas multiplication process and the variations in the initial ionization produced by homogeneous radiation. More recently, Byrne *et al* (1970) have studied the formation of avalanche chains generated by the release of single slow electrons in the argon-methane proportional counter by the pulse height analysis of the output produced by such a counter when it is illuminated with ultraviolet light.

Now from Einstein's photoelectric equation

$$h\nu = e\phi + \tfrac{1}{2} m v^2 \quad \dots \quad (1)$$

it is clear that the energy which the electrons acquire under the influence of light is $h\nu$, where h is the Planck's constant. It has evidently the same value for all electrons liberated by light of the same frequency, any difference in the Kinetic energy of the electrons emitted by monochromatic light must therefore be attributed to the effect of collisions of the escaping electrons in the interior of the substance Richardson & Compton (1912) measured the kinetic energy of the electrons emitted by various metals under the influence of light of different frequencies. They showed that if the maximum energy is a linear function of the frequency, the average energy or the most probable energy also bears a linear relation to the frequency. Incidentally, the photo electrons emitted by ultraviolet light exhibit in general velocity distribution which is Maxwellian in character. Earlier, Richardson & Brown (1908) had shown that the distribution of velocity among thermionically emitted electrons was identical with the Maxwellian distribution for a gas, of equal molecular weight to that of the electron at temperature of the metal Indeed, this was the first experimental demonstration of Maxwell's law although the law was predicted by Maxwell (1860) on theoretical grounds. Thus, we find that there is a close relationship between thermionic and photo-electric phenomena.

Sastri & Chatterjee (1967) investigated thermionic emission at low temperatures by counting the individual electrons produced within a Geiger counter. They verified Richardson's equation with as low a current density as of 3 electrons/cm^2.sec. It was next considered worth while to verify experimentally whether the electron avalanches produced in a proportional counter by thermionically emitted electrons exhibit any pulse-height distribution akin to Maxwellian distribution

2. Theoretical Consideration

It is known that the number of free electrons in a metal is of the same order of magnitude as the number of atoms, and so the electron cloud is very dense indeed. So dense is it that it cannot be assumed to behave like a perfect gas, although it is quite natural to speak of electron gas in a metal The energies of the electrons in this dense state are not divided according to the Maxwell formula, but according to the Fermic-Dirac formula based on quantum mechanics Accordingly, the distribution of energy in particles in such a dense state is given by

$$dN = \frac{3N}{2W_0^{3/2}} \frac{W^{\frac{1}{2}}dW}{[\exp((W-W_0)/kT)+1]} \quad \ldots \quad (2)$$

where
$$W_0 = \frac{h^2}{2m}\left[\frac{3N}{8\pi}\right]^{3/2}$$

N = number of electrons per unit volume
T = the absolute temperature

h is the planck's constant, m is the mass of the electron, W the kinetic energy of the electron and k the Boltzmann's Constant

The Fermi-Dirac distribution takes account of the fact that the electrons in a metal still possess energies at absolute zero- their atomic energies. None of them, however, have energies exceeding W_0 which for tungsten is 5.79 ev on the assumption that N is $6.33\times10^{28}/\text{metre}^3$. It may be noted that N varies slowly with T, and that $\bar{W}$ the mean value of W varies slowly with temperature due to large value of W_0 For temperatures below the melting point of most metals, it is a reasonable first approximation to assume that the total energy of a given aggregation of electrons in a metal does not change.

Another point of eq. (2) which calls for comment is its simplified form when W is greater that W_0. If $(W-W_0)/kT > 2$, then $e^{(W-W_0)/kT} \gg 1$ and therefore for high energy electrons in the metal the distribution is approximately given by

$$\delta N = \frac{3N}{2W_0^{3/2}} \cdot \exp(W_0/kT) \cdot \exp(-W/kT) \cdot W^{\frac{1}{2}}\,dW \qquad \dots \quad (3)$$

corresponding to the Maxwell distribution in form but not in magnitude.

When the temperature of a metal is raised, a larger proportion of free electrons in the metal acquire high velocities When the temperature is high enough, an appreciable number attain sufficient energy to escape from the metal entirely. But the work function of tungsten is 4 54 ev, and therefore electrons having energies in excess of 4.54 ev+5.79 ev = 10.33 ev may escape.

The total number of electrons per unit volume capable of escaping from the metal at any instant, as calculated by Thomson & Callick (1959) is

$$N_E = \left(\frac{2\pi mkT}{h^3}\right)^{3/2} \exp(-e\psi/kT) \qquad \dots \quad (4)$$

where ψ is the work function.

If $\bar{V}$ is the average energy of the escaping electrons, expressed in electron volts.

$$\bar{V} = \frac{1}{N_E} \int_0^\infty V\,dN$$

and $$\int VdN = \frac{4\pi m^2kT}{h^3} \int_0^\infty \left(\frac{eV}{2m}\right)^{\frac{1}{2}} \exp\left[\frac{-e(\psi+V)}{kT}\right] dV$$

This integral reduced to

$$\Gamma(3/2) = 1/2\Gamma(1/2) = \sqrt{\pi/2,} \text{ giving}$$

$$\bar{V}e = kT/2 \qquad \dots \quad (5)$$

using the value of N_E given by eq. (4).

Thus, for $T = 873°\text{K}$, $\bar{V} = 0.034$ volt

and $T = 928°\text{K}$, $\bar{V} = 0.04$ volt

The average escape energy of electrons in either case is only a small fraction of a volt. Such an electron finds itself in an electric field, whose intensity between two co-axial cylinders is given by

$$E = \frac{V}{r \log \dfrac{r_c}{r_a}}$$

where E is the electric intensity at a point distant r from the axis and is measured in volts per cm.

V is the potential in volts between the electrodes,

r_c—radius of the cathode

r_a—radius of the anode

This electron is accelerated toward the anode, and, where the field is sufficiently intense, will cause cumulative ionization if it collides with gas atoms or molecules as it moves towards the axial wire. In terms of the first Townsend Co-efficient α, the number of electrons n formed in cumulative avalanche by the single entering electron is given by

$$n = e^{\int \alpha dV} \tag{7}$$

The integral form of the exponent is required by the non-homogeneous electric field between the co-axial electrodes of the counter. Thus an avalanche, is triggered by a single electron in co-axial geometry. The corresponding pulse is also quenched by its own positive ion space charge. However, the ingredients of the data for generating pulses and their subsequent quenching are rendered somewhat obscure by the statistics of triggering which necessitates statistical analysis of complicated data to sort out fundamental variables. Accordingly, it was considered desirable to investigate the phenomenon experimentally and then analyse the results theoretically.

3. Experimental Method

The body of the proportional counter consisted of a brass tube, 10 cms long and 3.8 cms in diameter. The end pieces were fabricated from pyrex glass and fitted to the brass tube with Araldite, making vacuum tight joints. The central wire was of tungsten with a diametr 4 mil(0.1 mm). The uniformity of the wire was specially checked by means of a low power microscope, because a variation of uniformity reduces the resolving power of the instrument as a spectrometer. The actual positioning of the wire is not very critical, as indeed was demonstrated by Curran & Reid (1948)and Becker *et al* (1952). Rossi & Staub (1949) calculated that the extreme fractional difference of the field $\Delta E/E$ is given by the formula

$$\Delta E/E = 4ad/b^2 \tag{8}$$

where a = wire radius

b = cathode radius

and d = amount of displacement from the axis of the cylinder.

The offset wire consisted of a tungsten wire of diameter 6 mil (0.15 mm). It was kept taut while heated by means of a small tungsten spring. The tungsten leads were shielded by means of re-entrant glass tubes, which increased the insulation length of glass. Guard rings made of aquadag coating were inserted at appropriate places to prevent the arrival of disturbing currents at the central wire The offset wire was kept by an auxiliary battery at a potential, which was the same as that at points at the same distance from the central wire as the surface (of the offset wire) itself It was arranged that throughout the active volume of the counter, the field was radial as far as practicable. A schematic diagram of the proportional counter is depicted in figure 1. It was filled with a mixture of spectroscopically pure Argon (28 cms Hg) and pure Hydrogen (2 cms Hg) This was done to ensure a pulse size proportional to particle energy with a stabilizing influence on gas amplification.

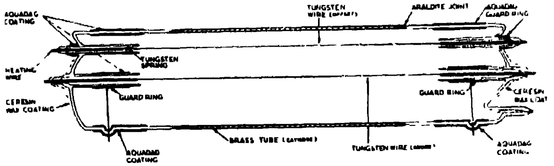

Fig. 1. Schematic diagram of the proportional counter.

Figure 2 shows a block diagram of the electronic circuit arrangement. Negative potential was applied to the cathode of the proportional counter by means

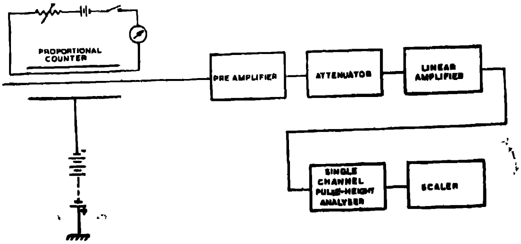

Fig. 2. Block diagram of the electronic circuit arrangement

of a H T. dry battery, in order to avoid minute voltage fluctuations of an electronically stabilised H.T. source This meant that the axial wire as the anode could be connected to the earth through a suitable resistor ($10^9\Omega$) eliminating thereby any complication due to the use of a coupling condenser. The axial wire was also directly connected to the suppressor grid of an Acorn 954, used as an electrometer tube as suggested previously by Gabus & Pool (1937) and Nielson (1947). To minimise or eliminate the various sources of grid current, it is necessary to operate with only +6 volts on the plate, so that no positive ions are produced in the vicinity of the grid, since electron energy is below the ionizing potential of the residual gas molecules. By operating the screen at a suitable positive voltage, no positive ions emitted by the cathode can reach the suppressor grid (working grid in the present arrangement). The customary control grid is connected to the cathode. The filament is operated at reduced temperature to further reduce the grid current. Photo-electrons are avoided by mounting the tube in a light tight box and surface leakage of current is restricted by coating the outer surface of the acorn tube with molten ceresin wax. Such an arrangement yields grid current of about 10^{-15} amp and behaves as the first stage of the pre-amplifier. The voltage amplification of this stage is, however, less than unity and operates as a current amplifier being a matching unit between the proportional counter having a high impedance and the second stage input of the pre-amplifier having a lower impedance. The latter is based on a three tube feed back loop with a maximum gain of 100 as suggested by Elmore & Sands (1949) The pre-amplifier in its turn is coupled to a linear amplifier having a gain of 10^5 through a cathode follower. The output from the main amplifier was connected to a single channel pulse height analyser (Philips Type PW 4082) for the analysis of pulse spectra The channel width adopted in the present set of experiments was 1 volt. Since the maximum channel height is 100 volts, the energy spectra could be spread into 100 channels. However, in the present experiment, it was found that the spectra could be scanned from the fifth channel at the low energy end because the earlier channels were, more or less marked by amplifier noise The spectra spread over to about thirty fifth channel at the high energy end The selected pulses, transmitted through various channels, were recorded by means of a scaler (Philips Type PW 4032) having five decade counting stages The amplifier assembly was previously calibrated by feeding a series of artificial pulses (from a signal generator) whose relative sizes are accurately known Thus one can express all the energy peaks in terms of signal generator output, thus avoiding the effects of any amplifier non-linearity. The gas amplification of the proportional counter as measured with the help of a calibrated signal generator was found to be about 4×10^4 in the present set of experiments

The temperature measurements of the heated wire was done with the help of a potentiometer circuit. A confirmation of the temperature attained by the wire was made by coating a small portion of the offset wire by Tempilaq° (manufactured by Tempil° corporation, U.S.A.) of appropriate m.p. and watching it from outside by means of a telemicroscope till it melted. The accuracy of this method is $\pm 1\%$.

4. Results and Discussion

Figure 3 shows the distribution of pulse-heights due to electron avalanches produced by thermionically emitted electrons within the proportional counter. Here δN, the number of avalanches recorded in a channel has been plotted against the channel number. Two different temperatures 873°K and 928°K were chosen for the generation of electrons for the purpose of measurement.

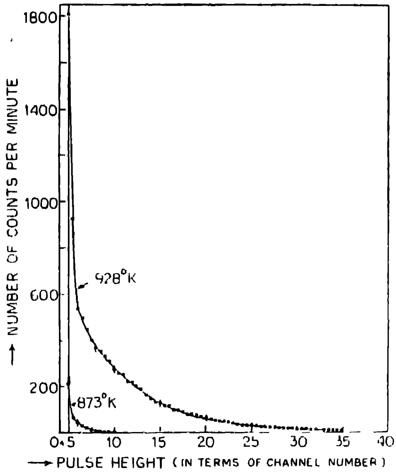

Fig. 3. Pulse height distribution of electron avalanches generated by thermionically emitted electrons in a proportional counter

The same data have been graphically represented in a logarithmic plot in figure 4, where log δN has been plotted against the channel number. It may be noted that the semi log plots ABC and $A'B'C'$ exhibit two different slopes with singularities at B and B' respectively. The steeper fragments AB and $A'B'$ incorporate a large number of short pulses and are confined within channel numbers 5 and 6. Normally this region was free from noise when the offset wire was not heated. The pulses appeared only when the wire was heated. Nevertheless, it was considered desirable to exclude this region from our analysis.

The pulse spectra as measured at 873°K and 928°K are given in Figure 3. The former gives an overall picture of the single electron avalanche pulse size distri-

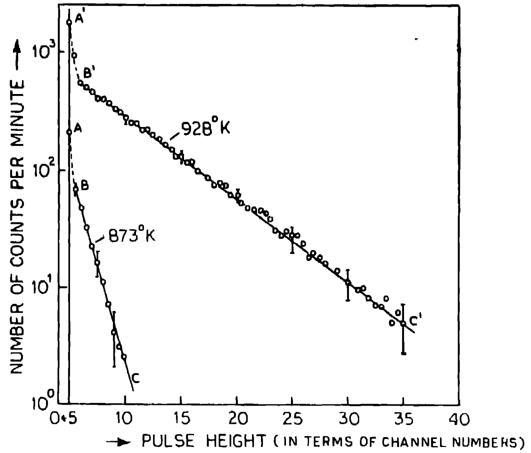

Fig 4. A logarithmic plot of the pulse height distribution of electron avalanches generated by thermionically emitted electrons in a proportional counter.

bution between 5 and 10 channel units, while the latter shows similar distribution between 5 and 35 units Apparently there is no maximum in either case, which agrees with the results of Bryne *et al* (1970)

An attempt was next made to fit the above-mentioned pulse-distribution curves with theoretical curves of the general form

$$X^{(a-1)}\exp(b-cX) \tag{8}$$

where a, b and c are empirical constants

A close fit was obtained with the experimental curve for 873°K with $a = 3.8$, $b = 6.4$ and $c = 1.2$, while the experimental curve for 928°K, the corresponding values of the constants were $a = 1.04$, $b = 7.1$ and $c = 0.153$. The proximity of the two sets of curvos is indicated in figuro 5, which also shows curran's pulse-height distribution for slow photo-electrons for the sake of comparision.

Taking into account the individual experimental data for number of pulses and their corresponding heights, one can calculate the mean pulse-height value $\bar{x}$ and root mean square deviation σ by the following relationships.

$$\bar{X} = \frac{\Sigma X_i f_i}{\Sigma f_i} \tag{9}$$

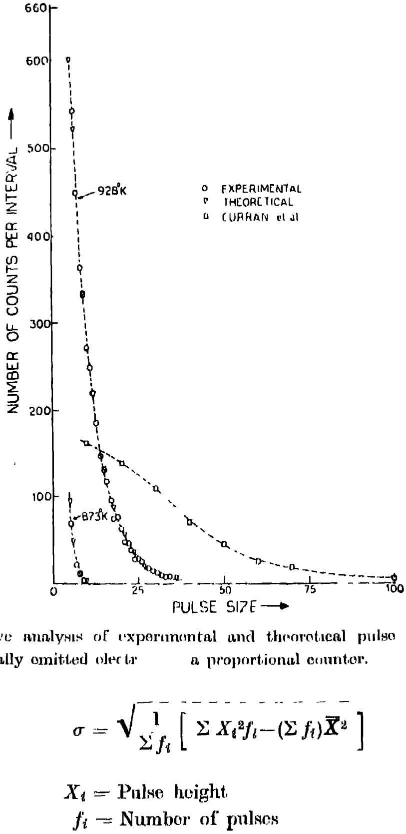

Fig 5 Comparative analysis of experimental and theoretical pulse size distribution for thermionically emitted electr a proportional counter.

and
$$\sigma = \sqrt{\frac{1}{\Sigma f_i}\left[\Sigma X_i^2 f_i - (\Sigma f_i)\overline{X}^2\right]} \quad \ldots \quad (10)$$

where X_i = Pulse height

f_i = Number of pulses

The corresponding values for 873°K are $\overline{X}_A = 6.3$ and $\sigma_A = 1.3$ while for 928°K, these are

$$\overline{X}_B = 15.1 \quad \text{and} \quad \sigma_B = 5\ 6$$

The mean values and the root mean square deviations of the two sets of theoretical distribution curves may be evaluated by utilizing the relations

$$\overline{X} = \frac{\int_0^\infty Xf(x)dx}{\int_0^\infty f(x)dx} \quad \ldots \quad (11)$$

$$\bar{X}^2 = \frac{\int_0^\infty X^2 f(x)dx}{\int_0^\infty f(x)\, x} \quad \ldots \quad (12)$$

and
$$\sigma^2 = \bar{X}^2 - \bar{X}^2 \quad \ldots \quad (13)$$

Thus, for the theoretical distribution curve for thermionically emitted electrons at 873°K

$$\bar{X}_{A'} = \frac{\int_0^\infty X^{3.8} \exp(6.04 - 1.2x)dx}{\int_0^\infty X^{2.8} \exp(6.04 - 1.2x)dx}$$

$$= (1.2)^{-4.8}\Gamma(4\ 8)/(1.2)^{-3\ 8}\Gamma(3.8)$$
$$= 4.0$$

and
$$\bar{X}^2_{A'} = \frac{\int_0^\infty X^{4.8} \exp(6.04 - 1.2x)dx}{\int_0^\infty X^{2.8} \exp(6\ 04 - 1.2x)dx}$$

$$= (1.2)^{-5.8}\ \Gamma(5.8)/(1.2)^{-3.8}\Gamma(3\ 8)$$
$$= 26\ 38$$

$$\sigma_{A'}^2 = \bar{X}_{A'}^2 - \bar{X}_{A'}^2 = 26\ 38 - 16\ 0 = 10.38$$

or
$$\sigma_{A'} = 3\ 2$$

So again, for the plse-height distribution curve for 928°K, we have

$$\bar{X}_{B'} = \frac{\int_0^\infty X^{1\ 04} \exp(7.1 - 0.153x)dx}{\int_0^\infty X^{0\ 04} \exp(7\ 1 - 0.153x)dx}$$

$$= (0.153)^{-2\ 04}\Gamma(2.04)/(0.153)^{-1.04}\Gamma(1.04)$$
$$= 6.8$$

and
$$\bar{X}_{B'^2} = \frac{\int_0^\infty X^{2\ 04} \exp(7\ 1 - 0.153x)dx}{\int_0^\infty X^{0.04} \exp(7.1 - 0.153x)dx}$$

$$= (0.153)^{-3.04}\Gamma(3\ 04)/(0.153)^{-1.04}\Gamma(1.04)$$

$$= 91$$

$$\sigma_{B'^2} = \bar{X}_{B'^2} - \bar{X}_{B'^2} = 91.0 - (6\ 8)^2 = 44.76$$

$$\sigma_{B'} = 6.7$$

The equation for the general normal distribution curve is

$$\gamma = \frac{NC}{\sigma\sqrt{2\pi}} \exp[-(x-\bar{x})^2/2\sigma^2] \tag{14}$$

Where
Y = number of counts per interval
N = total number of counts
C = interval between two consecutive pulse-heights
σ = root mean square deviation
X = pulse size
$\bar{X}$ = mean value of the pulse-size

Substituting the appropriate values of σ and $\bar{X}$ (obtained heretofore from the experimental data and from theoretical analysis) one can make a comparative study of the relevant normal distribution curves as shown in figure 6 They

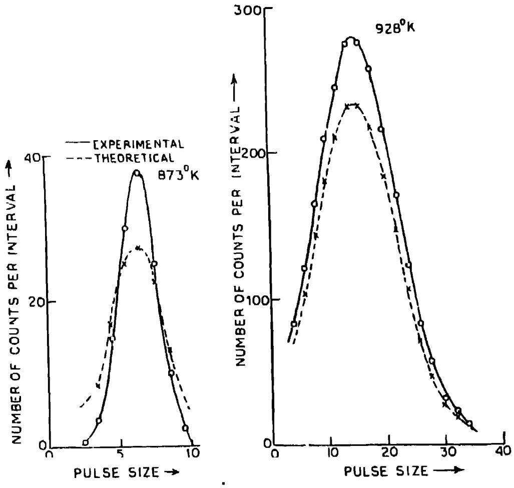

Fig 6. Analysis of line-width for thermionically emitted electrons at 873°K and 928°K

indicate that the line-widths of the thermionically emitted electrons at 873°K and 928°K respectively agree more or less satisfactorily with their theoretical analogues for mono-energetic electrons It signifies that the pulse-height distribution ,for electron avalanches produced by thermionically emitted electrons are closely similar to those produced by mono-energetic slow electrons. One therefore concludes that the energy distribution among thermionically emitted slow electrons should not be reflected in the pulse-height distribution of their corresponding avalanches in a proportional counter. This has been experimentally demonstrated by Curran *et al* (1949) and Byrne *et al* (1970) for slow photoelectrons generated within a proportional counter Indeed, they detected an increase in the amplitude of the mean pulse-height of the avalanches only when the voltage on the proportional counter was increased, which caused an increase of the gas amplification factor.

In the present case, however, it was found that the mean pulse-height increased from 6 3 at 873°K to 15 1 at 928°K, although the voltage on the proportional counter was maintained constant. A tentative explanation of the phenomenon may be given. With the commencement of the heating of the offset wire, there is a slight increase in pressure of the ambient gas enclosed within the proportional counter Subsequently, the axial wire absorbs more thermal radiation from the cathode than its surroundings In fact, the cylindrical geometry of the counter focusses the thermal radiation on the axial wire. This was experimentally verified by the measurements of the temperature of the axial wire. This was experimentally verified by the measurements of the temperature of the axial wire from the change of its resistance and that of the gaseous environment by means of micro-thermocouple probe. This increase in temperature of the axial wire established a radial thermal gradient in its neighbourhood and promotes bigger avalanche build up as postulated by Sastri and Chatterjee (1964) Alternatively, one comes to the dubious conclusion that the energy spectrum of thermionically emitted single electrons is somehow represented in their respective avalanche pulses in a proportional counter This is a point which needs more careful study

One notable feature about the monotone variation of the number versus pulse-height curves represented by BC and $B'C'$ in figure 4 may be due to the fact that the distribution could not be satisfactorily traced below the limit of amplifier noise. Indeed, the mean pulse-height cannot be determined without some residual uncertainty on account of the necessity of extrapolating to zero pulse-height as mentioned by Byrne *et al* (1970). The procedure carried out was therefore to omit the portions AB and $A'B'$ from our present analysis These two regions were located between channel numbers 5 and 6 which correspond with pulse-heights of 4.5 to 6 5 volts respectively which was free from noise pulses when the offset wire was not heated The preponderance of short pulses in this region has not been substantiated by Curran *et al* (1969) or Byrne *et al* (1970) in their studies of avalanche development for photo-electrons in Argon-methane proportional counters.

There are two main reasons why a noble gas, usually Argon is used in a proportional counter Firstly, Argon gives a low starting potential V_p, which is obviously advantageous. Secondly, its W value (amount of energy which an ionizing particle loses on the average to form one ion pair) is very closely independent of particle energy, which is an important consideration for accurate work. However, its tendency to excitation in metastable states due to photo-electric effect and the rapid rise of gas amplification in a proportional counter with increasing voltage precludes the use of the pure Argon gas. In order to meet both ends, a few per cent of a complex gas like methane is used Generally speaking, the more complex the added molecules, the more powerful is their effect in stabilizing the multiplication. However, addition of much methane endangers the constancy of the W value in Argon. On the other hand gases like hydrogen are particularly good in this respect In order to ensure a pulse size proportional to particle energy and a stabilizing influence on gas amplification, a mixture of argon and hydrogen was used in our proportional counter. Experimental determinations of the regenerative periods for avalanche chain formation by Jäger & Otto (1960) in Argon and by Lauer (1952) in hydrogen have established that the photo-electric process is by far the most effective in this respect. This increases the probability that an avalanche electron should generate a successor avalanche by photo-electric effect at the cathode as envisaged by Byrne (1970). It is possible that the smaller pulses incorporated in the region AB and $A'B'$ are due to single avalanches where as the bigger ones in the region BC and $B'C'$ are due to multiple avalanches

We have pleasure in thanking Dr. S R Ganguly, Department of Physics, Jadavpur University, for valuable help during the course of this investigation

References

Becker J., Chanson P., Nageotte E , Treille P , Price B T. & Rothwell P. 1952 *Proc Phys. Soc. Lond.* **A65**. 437.

Benson B. B 1946, *Rev Sci Inst* **17**. 533.

Byrne J , Shaikh F. & Kyles J. 1970, *Nuclear Inst, & Methods* **79** 286

Byrne J. 1970, *Physica* **17**. 38.

Curran S. C , Angus J & Cockroft A L 1949 *Phil Mag* 40 36 A 53

Curran S. C., Cockroft A. L & Angus J. 1949, *Phil. Mag.* **40** 929

Curran S. C. & Reid J. M. 1948, *Rev. Sci. Inst* **19**. 67.

Elmore W. C. & Sands H 1949, *Electronics—Experimental Techniques* pp 165 (McGraw Hill).

Gabus G. H & Pool H. L 1937, *Rev Sci. Ins.* 8. 196.

Hanna G C., Kirkwood D H. W. & Pontecorvo B 1949, *Phys. Rev.* **75**. 986.

Jager G. & Otto W. 1962 *Z. Physik* **169**. 517.

Lauer E. J. 1952, *J. App. Phys.* **23**. 301.

Maxwell J. C. 1860, *Phil. Mag.* **19**. 22.

Nielson C. E. 1947, *Rev. Sci. Inst.* **18**. 18.

Pontecorvo B , Kirkwood D. H W. & Hanna G. C. 1949, *Phys. Rev.* **75**. 982.

Richardson O. W. & Brown F. C. 1908, *Phil Mag.* **16**. 353.

Richardson O W. & Compton Karl T. 1912, *Phil Mag.* **24**. 575.

Rossi B. & Staub H. 1949, *Ionization Chambers and Counters* (McGraw Hill)

Thomson J. & Callick E. B. 1959, *Electron Physics & Technology*, pp. 31 (The English University Press, London).

Sastri R. C. & Chatterjee S. D. 1967, *Ind. J. Phys.* **41**. 793.

Sastri R, C, & Chatterjee S, D, 1964, *Zeit. f. Phys.* **177**. 562.